REPEATED WATER INJECTION EXPERIMENTS AT THE NOJIMA FAULT ZONE, JAPAN: INDUCED EARTHQUAKES AND TEMPORAL CHANGE IN FAULT ZONE PERMEABILITY

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A scientific drilling was carried out at the Nojima fault zone that ruptured during the 1995 Hyogo-ken Nanbu (Kobe) earthquake. Pressurized (3-4.5 MPa) water was repeatedly injected into the Nojima fault zone in 1997 and 2000 to monitor fault healing process on the basis of temporal change in permeability. We installed a temporary seismic network around the injection hole to monitor induced seismicity. Induced earthquakes were observed at the same region for the two injection experiments. The seismic activities started 4-5 and 6-7 days after the beginnings of injections in 1997 and 2000, respectively. The delay of two days suggests the decrease in permeability inside of the fault zone by 20-30 % due to fault healing. The following three characteristics of the induced earthquakes were derived from the present seismological studies: (1) Earthquake clusters composed of the induced earthquakes were also formed in the area with high seismicity at ordinary times. The activity reflects inhomogeneity in the crust, that is, low strength in the region; (2) The induced earthquakes in each cluster showed a gradual change in hypocentral distance at a certain station, reflecting successive rupture due to water migration in the low strength region; and (3) *B*-values of induced earthquakes were about 0.6. The values are extremely lower than those of natural earthquakes in the same area. The observed low *b*-value supports the idea that the water reduces the effective stress, causing induced earthquakes.

1. INTRODUCTION

The Nojima fault ruptured during the1995 Hyogo-ken Nanbu (Kobe) earthquake of *M*7.2 which occurred on January 17, 1995 (e.g., Nakata *et al.*, 1995; Awata *et al.*, 1996). A scientific drilling was carried out at the southwestern end of the Nojima fault after the mainshock (Ando, 2001). Three boreholes with depths of 500, 800, and 1800 m were drilled to the fault zone in the drilling project (Figure 1). Water was repeatedly injected into the 1800-m-deep borehole in 1997 and 2000 (Shimazaki *et al.*, 1998; Nishigami, 2001). The main purpose of the repeated water injection experiment is to monitor fault healing process, following the large earthquake, on the basis of temporal changes in permeability. Fault-valve action proposed by Sibson (1992) predicts that permeability in a fault zone is increased at a large earthquake and is decreased during the interseismic period, accompanying fault healing process. While water injection experiment were carried out and permeability were estimated also at Matsushiro region, Japan (Ohtake, 1974), and the KTB borehole, Germany (Zoback and Harjes, 1997), this is the first attempt to inject water repeatedly in the fault zone and to monitor temporal changes in permeability.

Outline of each water injection is summarized in Table 1. The water was intermittently injected to the borehole twice and three times in 1997 and 2000, respectively. The total amounts of injected water in 1997 and 2000 were 258 m^3 and 456 m^3, respectively. In the 1997 experiment, we maintained constant flow rate during each injection period. In the 2000 experiment, we controlled the flow rate to maintain constant values of pumping pressure.

Several geophysical observations were performed around the injection site. In this paper, we review findings derived only from seismological studies.

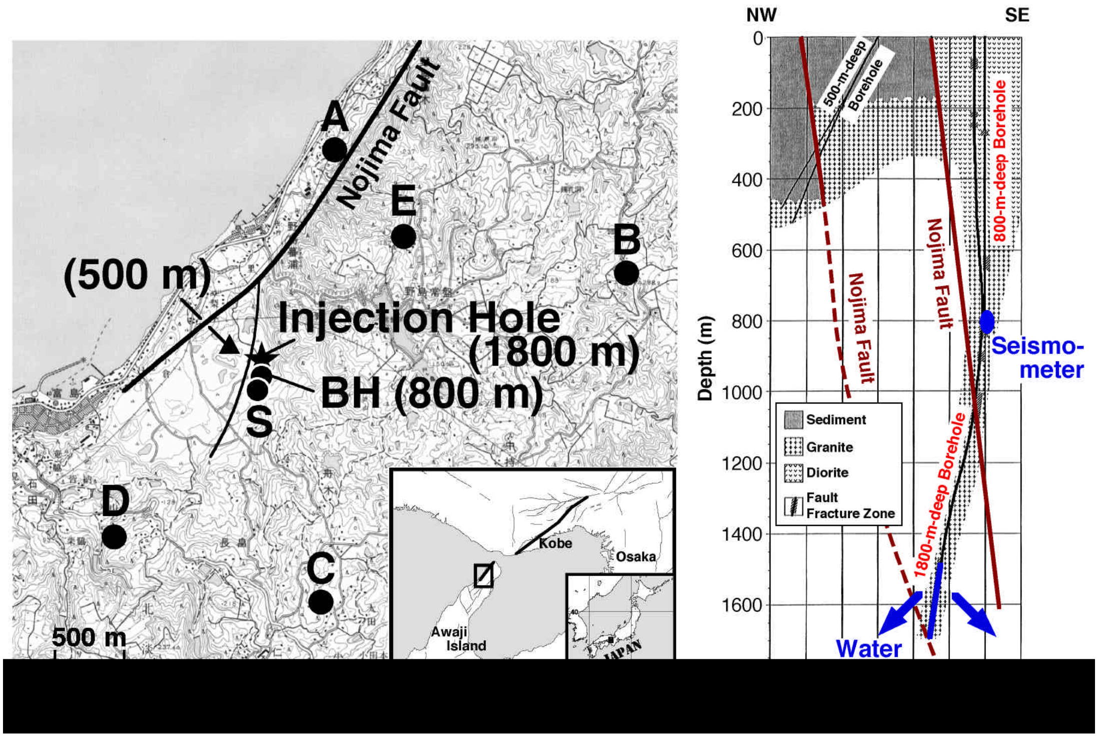

Figure 1. (Left) Map showing surface positions of the boreholes (denoted as 500 m, 800 m, and 1800 m) and distribution of the temporary seismic stations (solid circles; A-E, S, and BH). BH denotes the 800-m-deep borehole in which a three-component seismometer has been installed. Star denotes the injection hole (1800-m-deep borehole). (Right) NW-SE cross section of the Nojima fault and the boreholes (modified from Murata *et al*. 1997).

Table 1. Outline of the water injection experiments.

		Date	Period, hrs	Total Amount of Water, m^3	Pumping Pressure, MPa	Flow Rate, 10^{-3} m^3/min
1997	1st	Feb. 9-13	74	49	2.8 - 4.3	8-10, 15
	2nd	Mar. 16-25	216	209	4.0 - 4.7	16
2000	1st	Jan. 22-26	96	62.8	3.0	10-12
	2nd	Jan. 31-Feb. 5	120	119.9	4.0	16-18
	3rd	Mar. 3-11	192	273.0	4.5	20-26

2. SEISMICITY CAHGES AND PERMEABILITY IN THE FAULT ZONE

We installed a temporary seismic network around the injection hole to monitor seismicity changes (induced earthquakes) accompanying the water injection experiments (Figure 1). The network covered an area of 2 km × 4 km around the injection hole. A three-component seismometer has been installed also in the bottom of the 800-m-deep borehole. The seismometer records extremely high quality waveforms with high signal-to-noise ratio.

Figure 2 shows cumulative curves for earthquakes with *S-P* times less than 0.5 s at the 800-m-deep borehole station. In the 1997 experiment, obvious increases in seismicity were

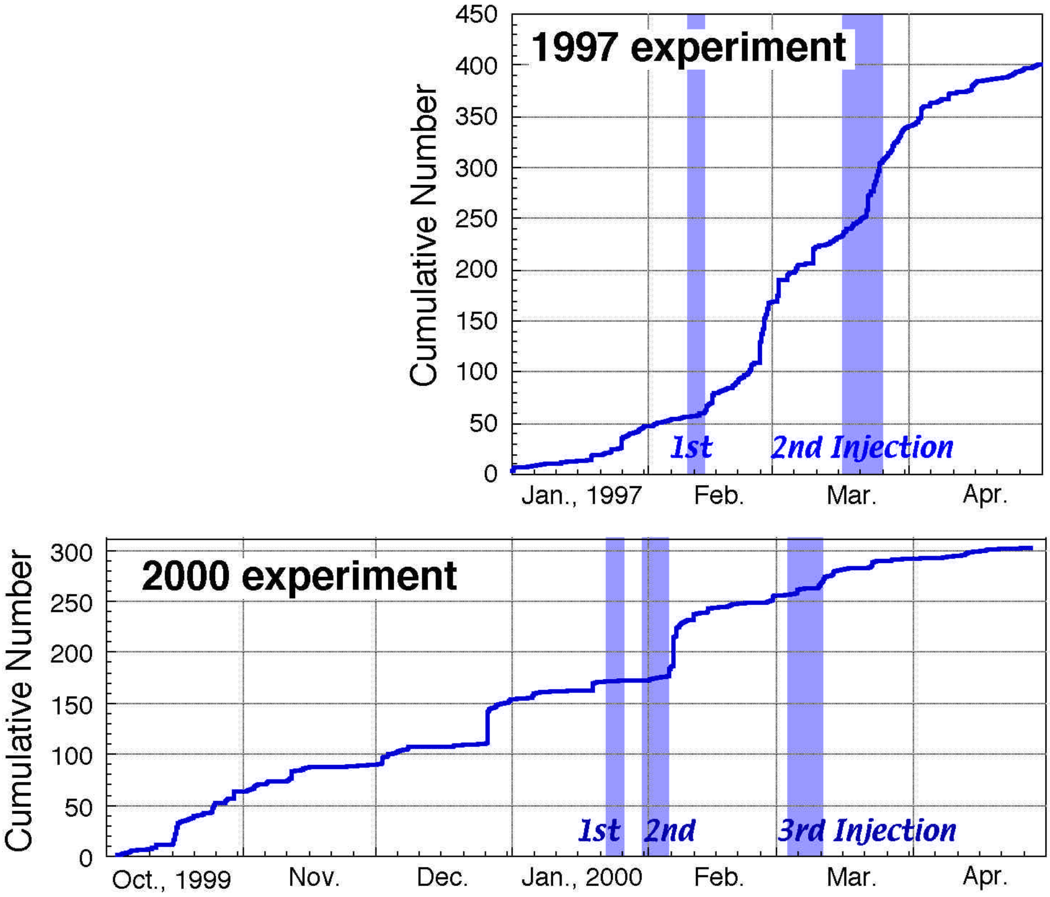

Figure 2. Cumulative curve for earthquakes with *S-P* times less than 0.5 s at the 800-m-deep borehole seismometer. Shaded sections indicate the periods of water injections.

observed at 4-5 days after the beginnings of each injection. We consider the increases in seismicity to have been induced by the injected water. The magnitudes of the induced earthquakes ranged from –2 to 1. The earthquakes occurred in the region about 3 km from the injection point and 2 to 4 km in depths (Tadokoro *et al*., 2000). We assume that the injected water has diffused inside of the permeable fault zone. Under the assumption, the time interval between the beginning of injection and the timing of abrupt increase in seismicity reflects the permeability of the fault zone. Solving a diffusion equation, the permeability of the Nojima fault zone in 1997 is estimated to be 10^{-14}-10^{-13} m^2 (the detailed procedure for the calculation is mentioned in Tadokoro *et al*. (2000)). In the 2000 experiment, while induced earthquakes were also observed at the same region as the 1997 experiment (Nagai *et al*., 2001; Tadokoro *et al*., 2001), the induced seismicity started 6-7 days after the beginnings of each injection. The time interval is two days longer than that in 1997. The delay of the two days implies decrease in permeability in the fault zone due to fault healing. Adopting the same procedure as the 1997 experiment, the permeability in the Nojima fault zone is estimated to have decreased by 20-30 % between the three years (Tadokoro *et al*., 2001).

3. CHARACTERISTICS OF THE INDUCED EARTHQUAKES

3.1. EARTHQUAKE CLUSTER AND HYPO-CENTER MIGRATION

We observed some groups of earthquake with similar waveform (Figure 3). The waveform

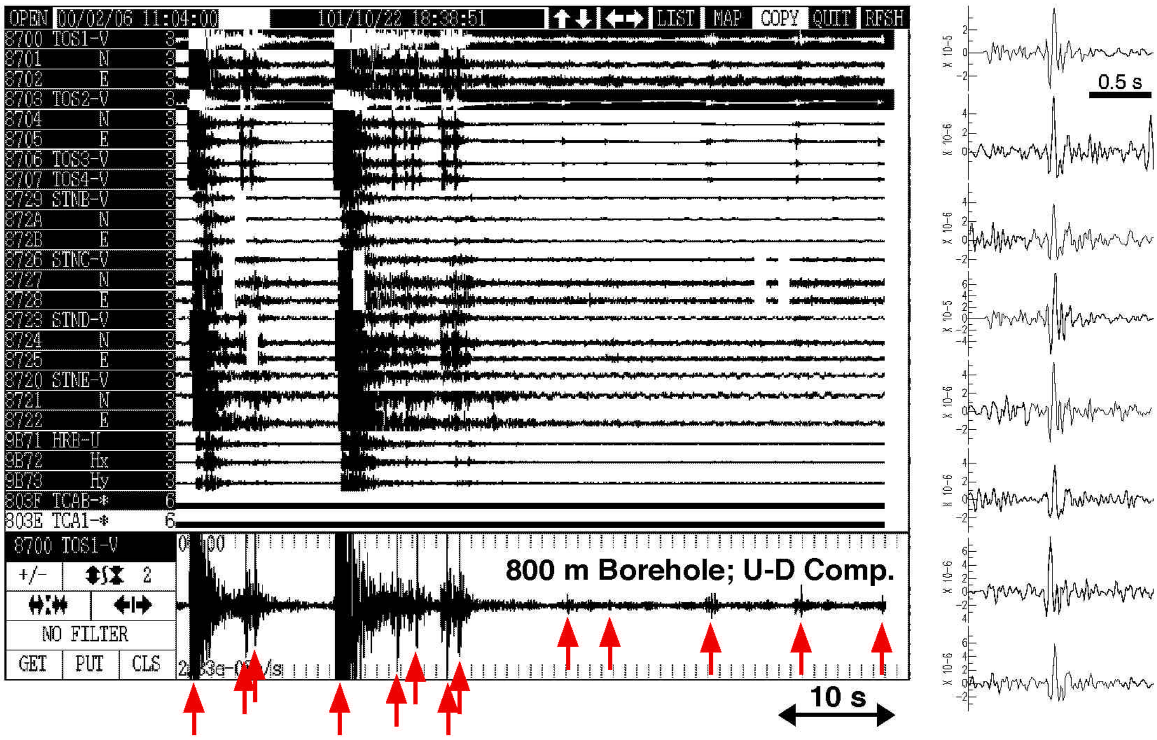

Figure 3. Example of clustered seismic activity. (Left) Continuous seismograms for one minute from 11:04:00 (JST), February 6, 2000. Each earthquake is pointed by red arrow. (Right) Enlarged U-D component seismograms of eight earthquakes with relatively large amplitude among 13 earthquakes in left figure. All the earthquakes have similar waveform.

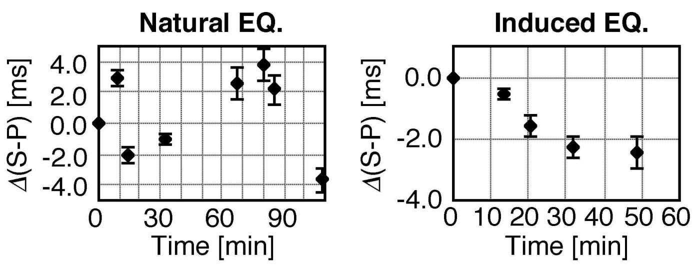

Figure 4. Typical patterns of hypocenter migration (temporal changes in *S-P* time) in a cluster for natural (left) and injection-induced (right) earthquakes. Vertical axis is the *S-P* time difference with a reference earthquake. Horizontal axis is the relative time.

similarity suggests that those earthquakes have occurred very close to each other in space, forming an earthquake cluster. The clustered seismic activities were shown among the induced earthquakes in 1997 and 2000 as well as the natural earthquakes. Most of the earthquake clusters were formed within two hours. In the cluster shown in Figure 3, 21 earthquakes occurred only in two minutes.

We made a cross-spectrum analysis using the waveforms recorded at the 1800-m-deep borehole station to discuss hypocenter migration in each earthquake cluster on the basis of temporal changes in *S-P* time (Tadokoro *et al.*, 2000). This analysis is favorable to detect slight changes in *S-P* time, even if the changes are 10 ms or less (e.g., Ito, 1985, 1990). Figure 4 shows the typical patterns of hypocenter migration (temporal changes in *S-P* time). There is an obvious difference in migration pattern between the natural earthquakes and the induced earthquakes. The natural earthquakes show no systematic change in *S-P* time. On the other hand, the value of *S-P* time monotonously (gradually) changes with time for the induced earthquakes. The

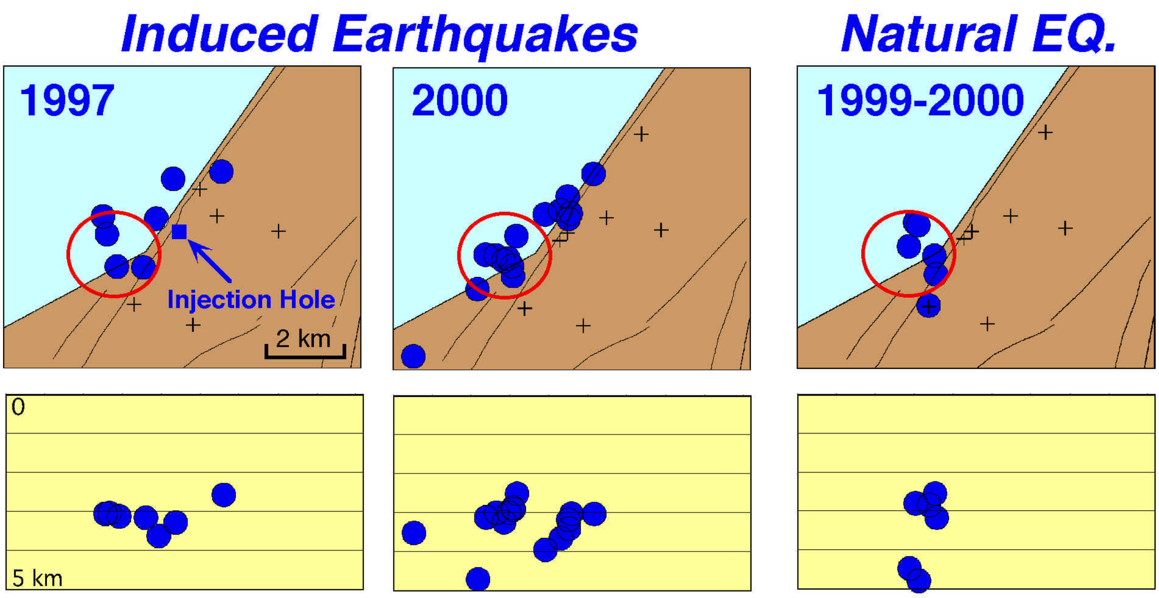

Figure 5. Map views and cross sections showing the locations of earthquake clusters. The hypocenters of largest earthquake in each cluster are plotted (blue solid circles). Earthquake clusters concentrated in the area denoted by red circle.

monotonous changes in *S-P* time, representing systematic migration of hypocenters, are likely to reflect successive rupture due to migration or permeation of water. The clustered natural earthquakes just occurred separately in the small region. The maximum *S-P* time differences in a cluster ranged from 3 to 20 ms, which indicates that the total rupture size of a cluster is at least ~20-160 m.

Figure 5 shows the locations of the earthquake clusters. The earthquake clusters composed of the induced earthquakes concentrated in the same area (denoted by the red circles in Figure 5) as the natural earthquakes. This phenomenon suggests that this region can rupture with an extremely small increment in shear stress or pore pressure, that is, the strength in this region is low in comparison with that in its surroundings. According to the water migration inferred from the above-mentioned cross-spectrum analysis, the low strength may be caused by well-developed fracture system (extremely high fracture density). The injected water migrated in the fracture system, connecting pre-existed fractures, and forced the low strength region to induce the concentrated seismic activities.

3.2. *B*-VALUE

We estimated *b*-values, applying the maximum likelihood method proposed by Aki (1965) (Kano *et al.*, 2001). The *b*-values of induced earthquakes are about 0.5-0.6. The values are obviously lower than those of the natural earthquakes in the same area (Table 2, Figure 6).

Induced seismic activities are generally explained by decrease in effective stress due to pore pressure increase. Scholz (1968) proposed a model that explains his experimental results that *b*-values of acoustic emissions decrease with the increase of effective stress. The model assumes that (1) when uniform stress, $\bar{\sigma}$, is applied to an inhomogeneous medium, the local stress, σ, is random and can be defined by a probability density function, $f(\sigma; \bar{\sigma})$,

Table 2. Comparison of *b*-values.

Year	*B*-value	
	Induced Earthquake	Natural Earthquakes
1997	0.53±0.20	0.74±0.25
2000	0.66±0.21	0.91±0.37

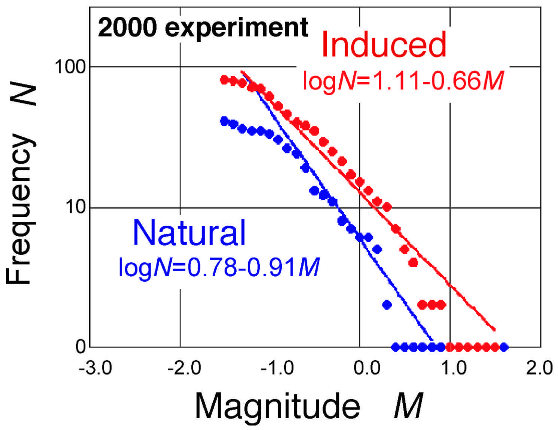

Figure 6. Frequency (number of earthquakes; *N*)-magnitude (*M*) distribution for the natural earthquakes and the induced earthquakes observed in 2000. Lines of regression are obtained by the maximum likelihood method (Aki, 1965).

and (2) A fracture will proceed in regions where the local stress exceeds the strength, *S*. The probability that the fracture will exceed is represented by integration of $f(\sigma;\ \bar{\sigma})$ over σ from 0 to *S*, $F(S;\ \bar{\sigma})$. Then, the probability that the fracture will stop is expressed as $1\text{-}F(S;\ \bar{\sigma})$ (Figure 7). He showed that *b*-value is proportional to $1\text{-}F(S;\ \bar{\sigma})$. We can explain our result that *b*-values decreased for the induced earthquakes, introducing Scholz's model with the effect of pour pressure change: when the strength *S* decreases because of increase in pore pressure, the probability that the fracture will stop, $1\text{-}F(S;\ \bar{\sigma})$, decreases, resulting in low *b*-value.

4. DISCUSSION AND CONCLUSIONS

We performed the repeated water injection experiment at the Nojima fault, Japan in 1997 and 2000. The induced earthquakes were observed at the same region for the two injection experiments. The estimated permeability in the fault zone decreased by 20-30 % between 1997 and 2000, which reflecting fault healing process.

The occurrence mechanism of injection-induced earthquakes has been explained by the propagation of increased pore pressure (Hubbert and Rubey, 1959). This explanation is, however, accepted for the macro-scale phenomena with sizes of several kilometers. The results of the cross-spectrum analysis suggest that the hypocenter migration with

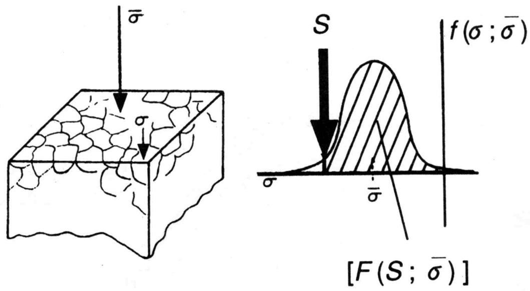

Figure 7. (Left) Schematic illustration showing the response of an inhomogeneous medium to a uniform applied stress $\bar{\sigma}$. (Right) An arbitrary form of $f(\sigma;\ \bar{\sigma})$, describing the probability that the stress at a point is σ. *S* is the average local strength. (Modified from Scholz, 1968).

micro-scale (at orders of ten to hundreds meters) reflects the successive rupture in the low strength region, produced by well-developed fracture system, due to the migration of water itself with connecting pre-existed fractures. Investigations into clustered activities of injection-induced earthquake provide information on inhomogeneity in the crust, or rather, contrast of crustal strength.

The low *b*-values observed for the induced earthquakes support the idea that the water reduces the effective stress, causing induced earthquakes.

We have a plan to perform a water injection experiment again in 2003 for continuous monitoring of permeability reduction, and to investigate detailed mechanism of earthquakes induced by pressurized water.

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